Physics Motivation

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Fermilab

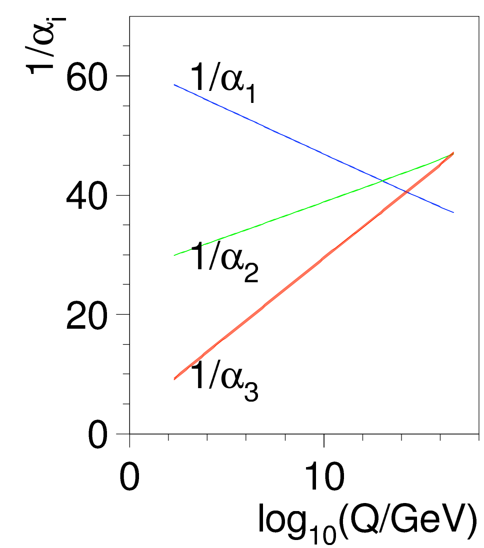
Physics Landscape

- All data consistent with Standard Model - but it's incomplete
  - dark matter; neutrino masses and mixing -> new fields or interactions; baryon asymmetry -> more CP violation
- Theoretical questions
  - The issue of naturalness and the origin of mass;
    - $\mu^2 (\Phi^\dagger\Phi) + \lambda (\Phi^\dagger\Phi)^2 + \Gamma_{ij}\psi_{iL}{}^\dagger\psi_{jR}\Phi$ + h.c.

$m_H{}^2/M^2{}_{planck} \approx 10^{-34}$ Hierarchy problem

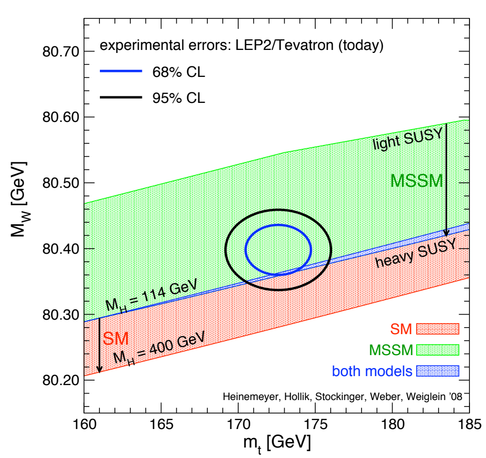
vacuum stability

large range of fermion masses

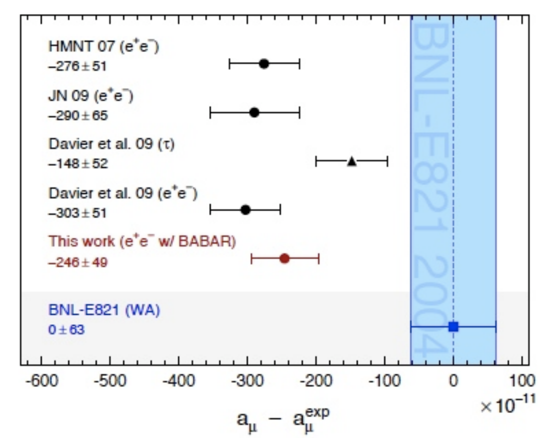


  - gauge unification -> new interactions;
  - gravity: strings and extra dimensions
- Experimental hints for new physics

Higgs



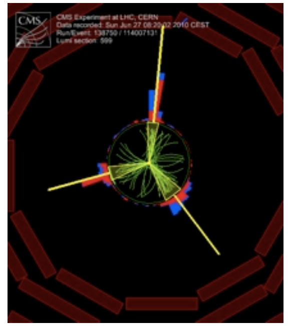
muon (g-2)



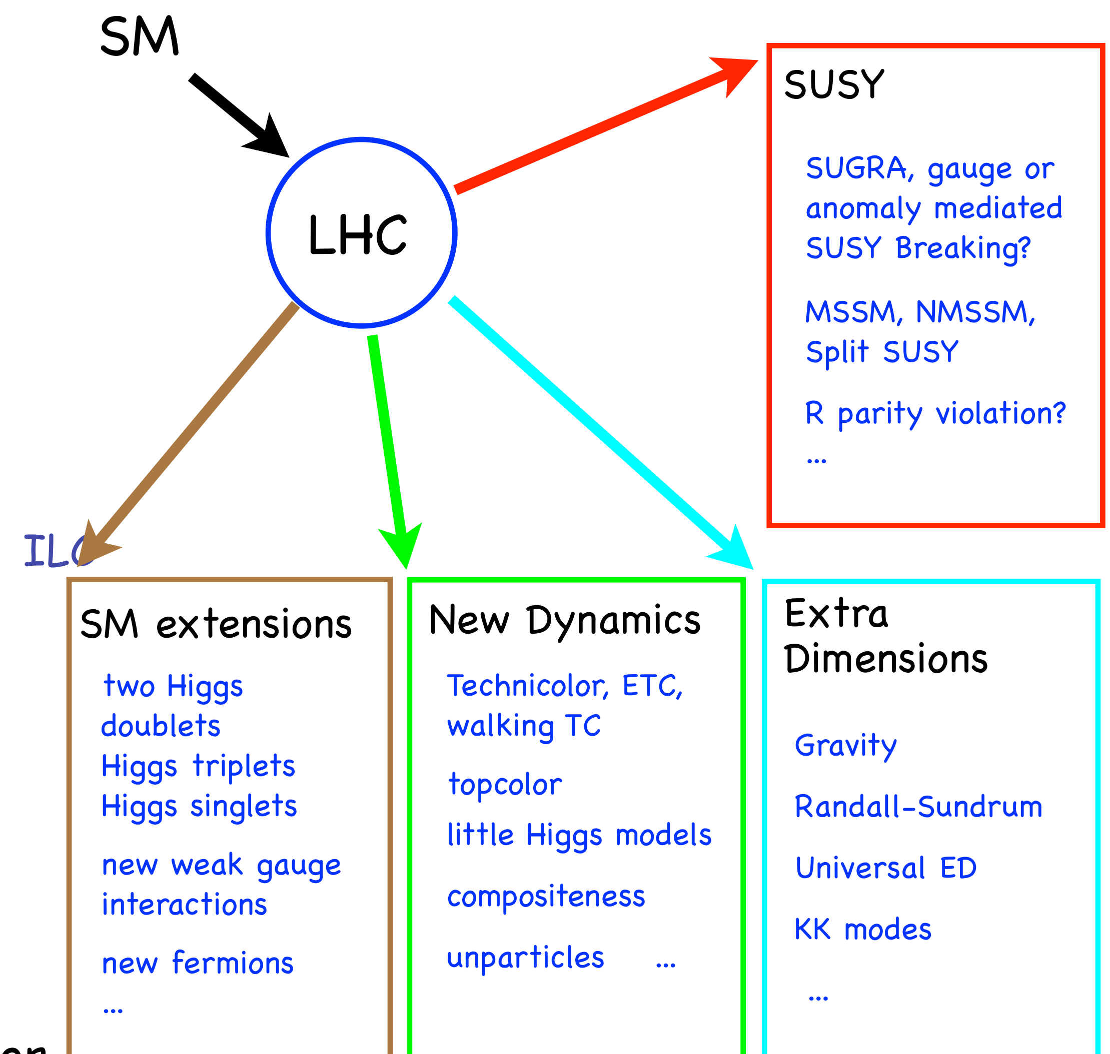
Crossroad In Theoretical Physics

- LHC online

  $\sqrt{s}$ = 14 TeV   p p
  Luminosity - 10^{34} cm^{-2} sec^{-1}
  ATLAS, CMS, LHCb, ALICE

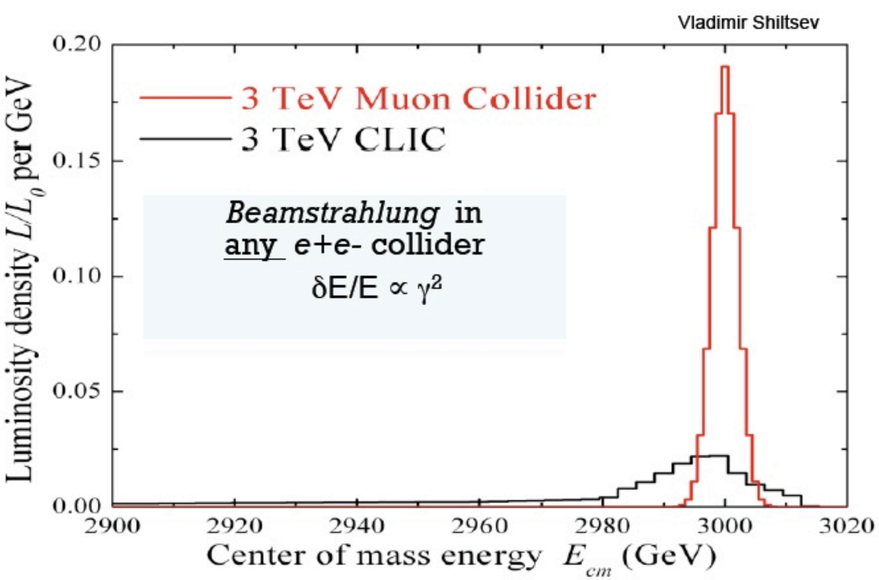


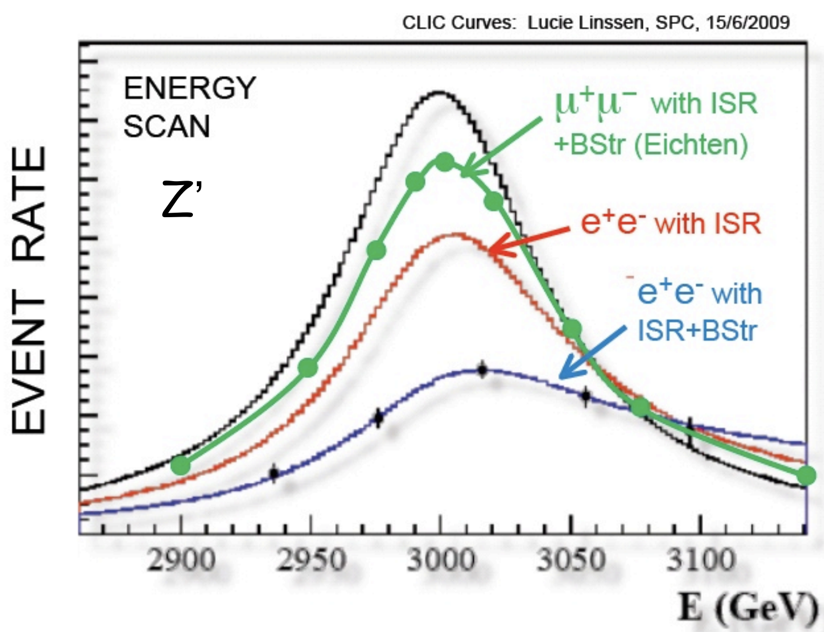
- Existing facilities in 2025:
  - LHC with luminosity or energy upgrade
- Options:
  - low energy lepton collider: (500 GeV) (upgradable) or muon collider - Higgs Factory
  - lepton collider in the multi-TeV range: CLIC or muon collider
  - hadron collider in hundred TeV range: VLHC
- High energy lepton collider required for full study of Terascale physics.



A Muon Collider

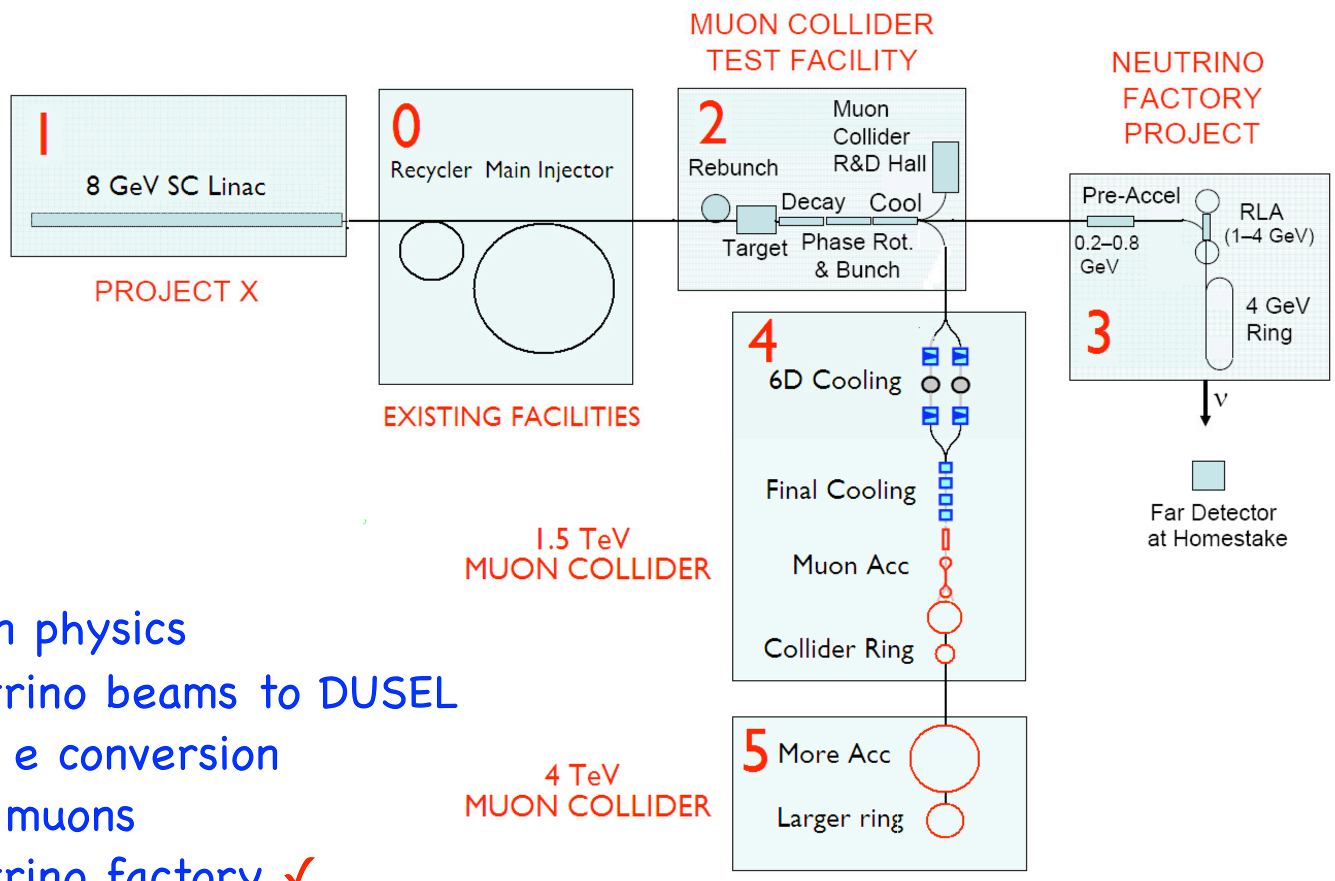
- $\mu^+\mu^-$ Collider:
  - Center of Mass energy: 1.5 - 5 TeV (focus 3 TeV)
  - Luminosity > 10^{34} cm^{-2} sec^{-1} (focus 400 fb^{-1} per year)
- Compact facility
- Superb Energy Resolution
  - MC: 95% luminosity in dE/E ~ 0.1%
  - CLIC: 35% luminosity in dE/E ~ 1%





Path to Muon Collider Facility

- A flexible scenario with physics at each stage:



- Kaon physics
- Neutrino beams to DUSEL
- μ -> e conversion
- cold muons
- Neutrino factory ✓
- Muon collider - Higgs factory ✓
- Multi-TeV Muon Collider ✓

Neutrino Physics

- SM leptons: $\mathsf{L}_e = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_{\mathrm{L}}$ $\mathsf{L}_\mu = \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_{\mathrm{L}}$ $\mathsf{L}_\tau = \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_{\mathrm{L}}$ $\mathsf{R}_{e,\mu,\tau} = e_{\mathrm{R}}, \mu_{\mathrm{R}}, \tau_{\mathrm{R}}$

  No ν_R needed. Singlet under $SU(3)_c \times SU(2)_L \times U(1)_Y$
  Lepton number conserved.

- Observation of neutrino flavor mixing drastically changes the picture

- Flavor mixing ⇒ neutrino masses
  - Solar neutrinos
  - Atmospheric neutrinos

$$\Delta m^2_{\mathrm{solar}} << \Delta m^2_{\mathrm{atm}}$$

Simple two flavor (α,β) case: with mass eigenstates (i,j)

$$\nu_\alpha = \nu_i \cos\theta + \nu_j \sin\theta$$

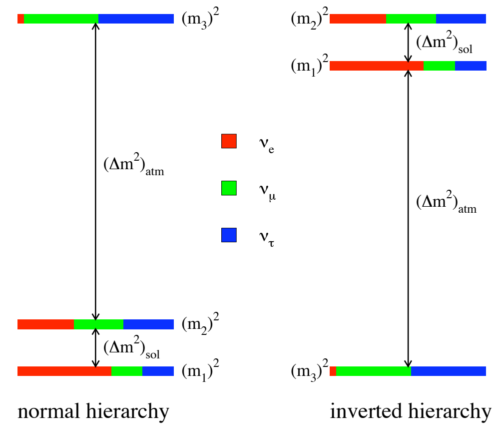
$$\nu_\beta = -\nu_i \sin\theta + \nu_j \cos\theta$$

$$P_{\alpha\to\beta} = \sin^2 2\theta \sin^2\left(\Delta m^2 L/4E\right)$$

Oscillation probability (P) for energy (E) and distance (L)

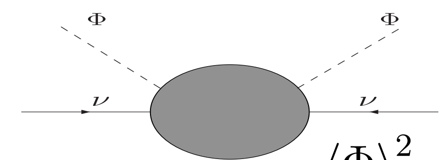
Theoretical Issues

- Normal or Inverted Mass Hierarchy?



- Majorana or Dirac particles?
  - Majorana: no ν_R - mass term violates lepton number conservation $\mathcal{L}_{\rm mass} = \bar{\nu}_L^c M_L \nu_L + h.c.$
  - Dirac: ν_R $\mathcal{L}_{\rm mass} = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}^\dagger \mathcal{M} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} + h.c.$

$\mathcal{M}$: Pure Dirac: $\begin{pmatrix} 0 & M \\ M^\dagger & 0 \end{pmatrix}$ Seesaw: (I) $\begin{pmatrix} 0 & M \\ M^\dagger & M_R \end{pmatrix}$ (II) $\begin{pmatrix} M_L & M \\ M^\dagger & M_R \end{pmatrix}$



$$m_\nu = \lambda_0 \frac{\langle \Phi \rangle^2}{M_X}$$

  - Does ν_R have new gauge interactions?

- Three generation mixing matrix: PMNS

Pontecorvo-Maki-Nakagawa-Sakata Matrix

Three angles: $\theta_{12}, \theta_{23}, \theta_{13}$ CP phases: δ(Dirac) (α,β,δ)(Majorana)

$$\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} = U_{\rm PMNS} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix}$$

The additional Majorana CP phases appear in lepton number violating interactions: eg. neutrinoless double beta decay.

$$\mathrm{U_{PMNS}} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} diag(1, e^{i\alpha/2}, e^{i\beta/2})$$

$c_{ij} = \cos(\theta_{ij})$ $s_{ij} = \sin(\theta_{ij})$

Experimental Status

- Present status

T. Schwetz, M. Tortola and J. Valle

[arXiv:0808.2016v3] update

parameter	best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.59^{+0.23}_{-0.18}$	7.22–8.03	7.03–8.27
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.318^{+0.019}_{-0.016}$	0.29–0.36	0.27–0.38
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.013^{+0.013}_{-0.009}$	≤ 0.039	≤ 0.053

KamLAND

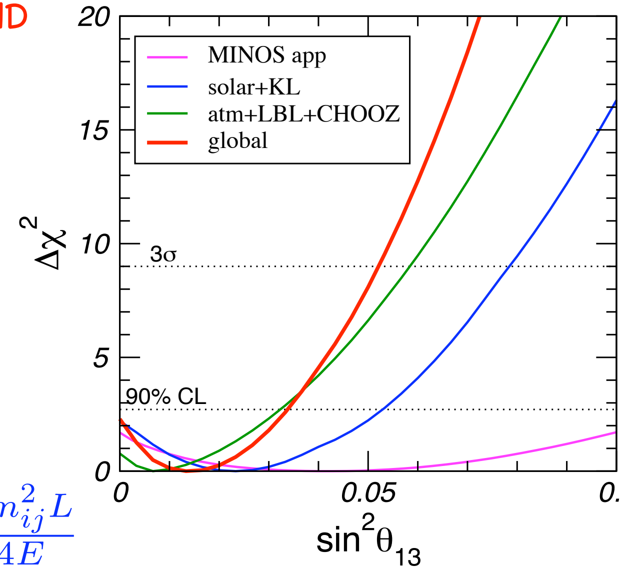
K2K,

MINOS

SNO

SuperK

CHOOZ



- $\sin^2\theta_{13}$, δ not yet measured

$$\Delta_{ij} \equiv \frac{\delta m^2_{ij} L}{4E}$$

- Reactor Neutrinos: Daya Bay, Double CHOOZ, Reno

Atmos. L/E $\mu \to \tau$ Atmos. L/E $\mu \leftrightarrow e$ Solar L/E $e \to \mu, \tau$

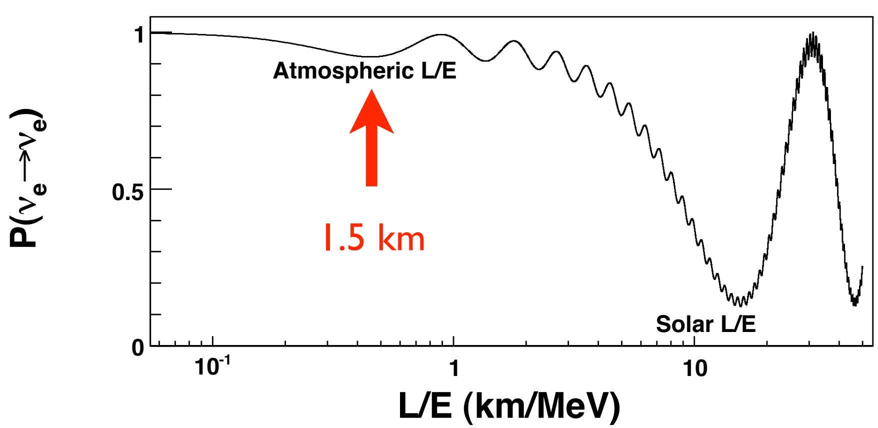
500km/GeV 15km/MeV

$$P(\bar\nu_e \to \bar\nu_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

< 0.002

$$\approx \quad 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\delta m^2_{ee}L}{4E}\right) - \mathcal{O}(\Delta_{21})^2$$

Daya Bay sensitivity ≈ 0.01



Long Baseline Experiments

- Appearance

where $\Delta_{ij} \equiv |\Delta m^2_{ij}| L/4E$

$$\sqrt{P_{\rm atm}} = \sin\theta_{23}\sin 2\theta_{13}\left[\frac{\Delta_{31}\sin(aL\mp\Delta_{31})}{(aL\mp\Delta_{31})}\right]$$

$$\sqrt{P_{\rm sol}} = \cos\theta_{23}\sin 2\theta_{12}\left[\frac{\Delta_{21}\sin(aL)}{aL}\right]$$

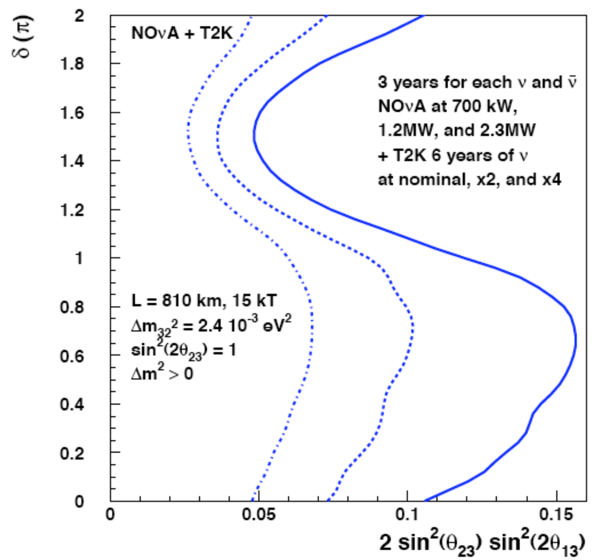
  - Nova and T2K

$$P(\nu_\mu \to \nu_e) \approx |\sqrt{P_{atm}}e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{solar}}|^2$$

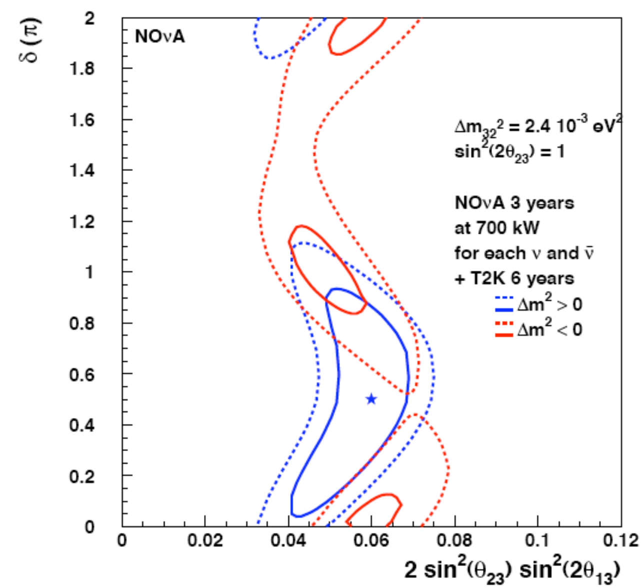
  - Index of refraction in matter: $a = G_F N_e/\sqrt{2} \approx (4000\ \text{km})^{-1}$
  - The interference term is the only term that depends on CP phase δ; also the only term that differs for neutrino/antineutrino beside the matter effects.

Resolving the mass ordering.

inverted order ($\delta \to \pi - \delta$)



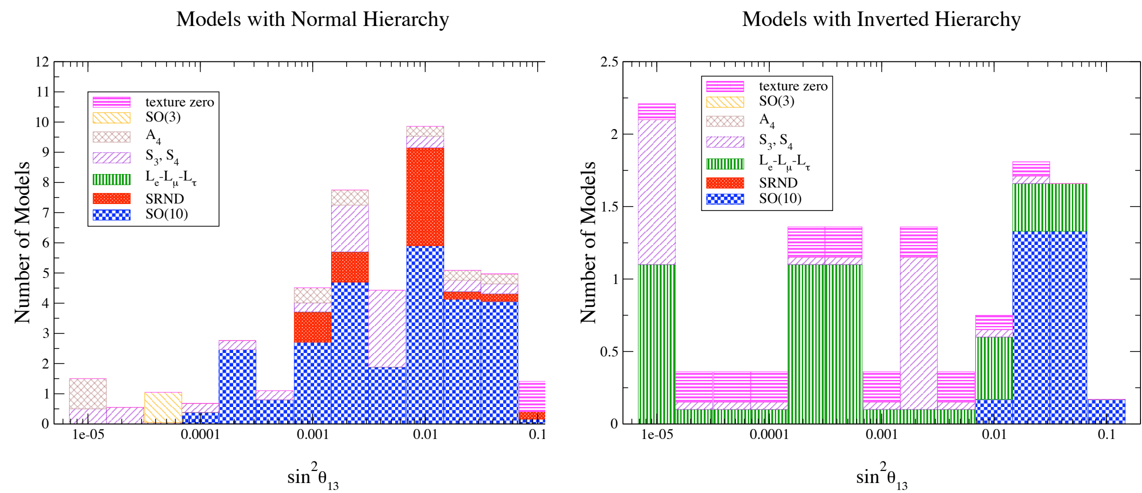
Normal Ordering



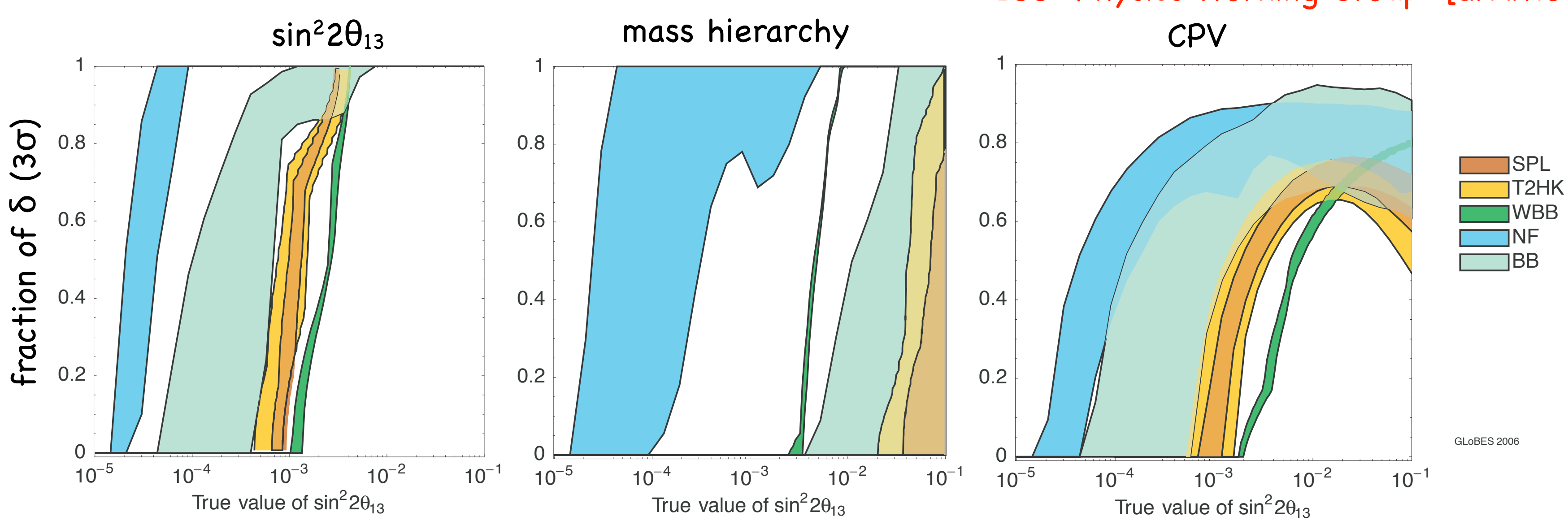
  - Complicated to disentangle θ_{13}, δ and mass ordering

Neutrino Factory

- No theory for the value of $\sin^2\theta_{13}$
- Neutrino factory:
  - Muon storage ring: E = 25 GeV
  - Long straight sections
  - High intensity: 10^{21} muon decays /yr
- Discovery reach for various propos



ISS Physics Working Group [arXiv:0710.4947]



Very likely a Neutrino Factory will be needed to provide detailed measurements of θ_{13}, the mass hierarchy and the CPV parameter δ.

Muon Collider Basics

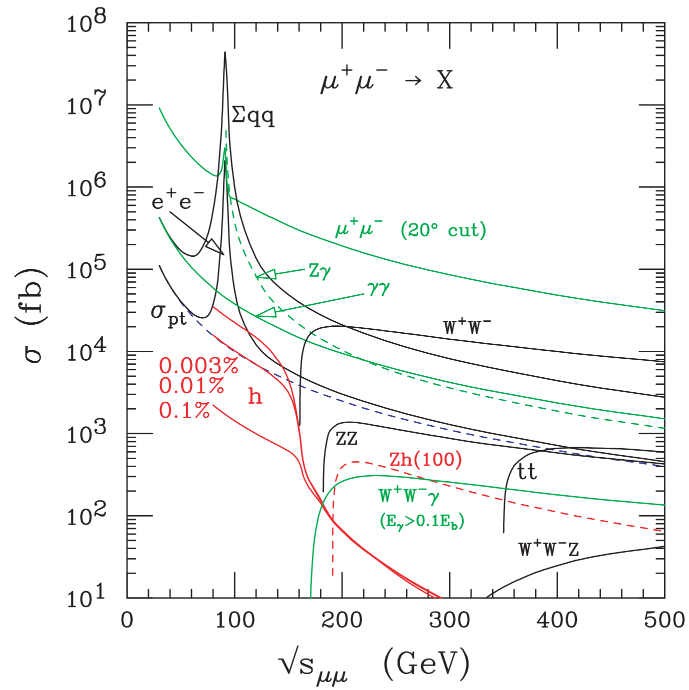
- For $\sqrt{s}$ < 500 GeV
  - SM threshold region: top pairs; W^+W^-; Z^0Z^0; Z^0h; ...
- For $\sqrt{s}$ > 500 GeV
  - For SM pair production ($|\theta| > 10°$)

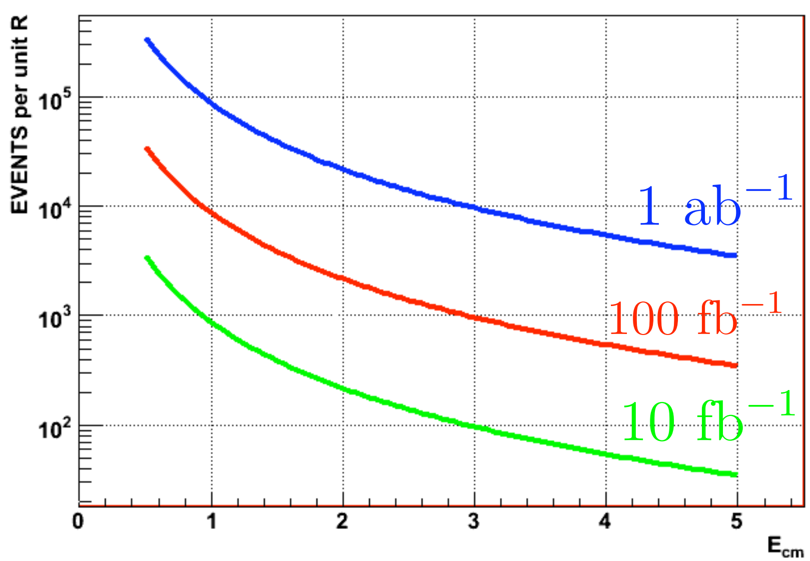
    R = $\sigma / \sigma_{QED}(\mu^+\mu^- \to e^+e^-)$ ~ flat

$$\sigma_{\rm QED}(\mu^+\mu^- \to e^+e^-) = \frac{4\pi\alpha^2}{3s} = \frac{86.8\ \rm fb}{s(\rm TeV^2)}$$

  - High luminosity required

Standard Model Cross Sections





$$\sqrt{s} = 3.0\ \text{TeV} \qquad \mathcal{L} = 10^{34}\ \text{cm}^{-2}\text{sec}^{-1} \to 100\ \text{fb}^{-1}\text{year}^{-1}$$

$\Rightarrow$ 965 events/unit of R

Processes with R ≥ 0.1 can be studied

Total - 540 K SM events per year

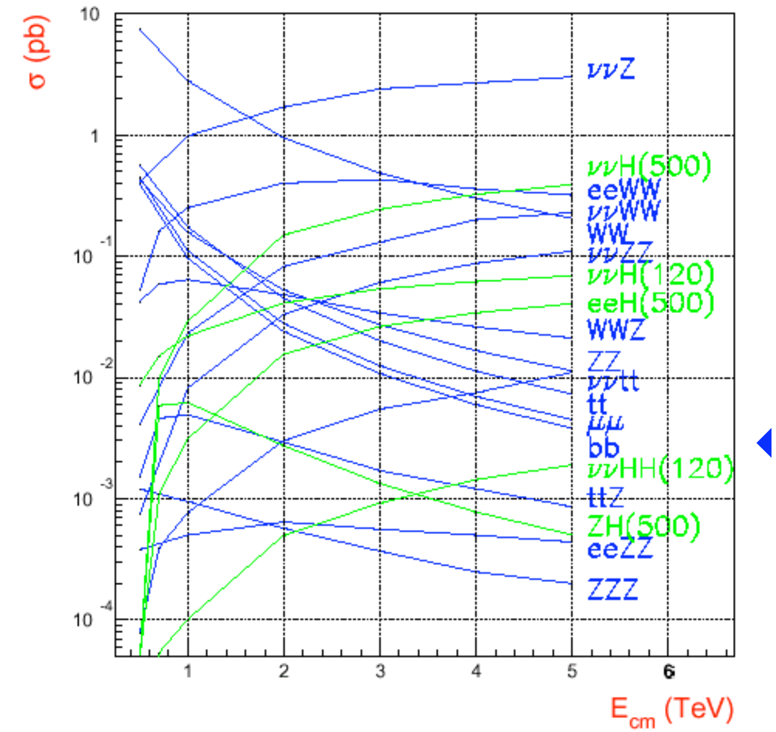
Muon Collider Basics

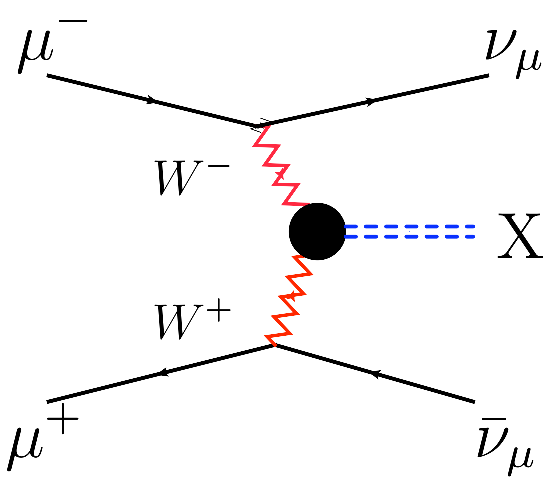
- For √s > 1 TeV - Fusion Processes

  - Large cross sections
  - Increase with s.
  - Important at multi-Tev energies
  - $M_X^2 < s$

  • Backgrounds for SUSY processes
  • t-channel processes sensitive to angular cuts

CLIC (or MC e<->μ)





$$\sigma(s) = C \ln(\frac{s}{M_X^2}) + \ldots$$

- An Electroweak Boson Collider

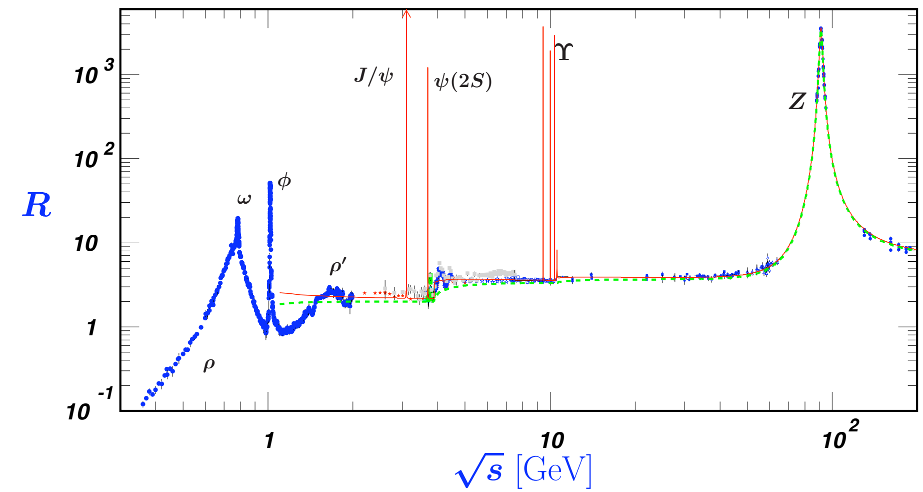
Minimum Luminosity for Muon Collider

- Universal behavior for s-channel resonance

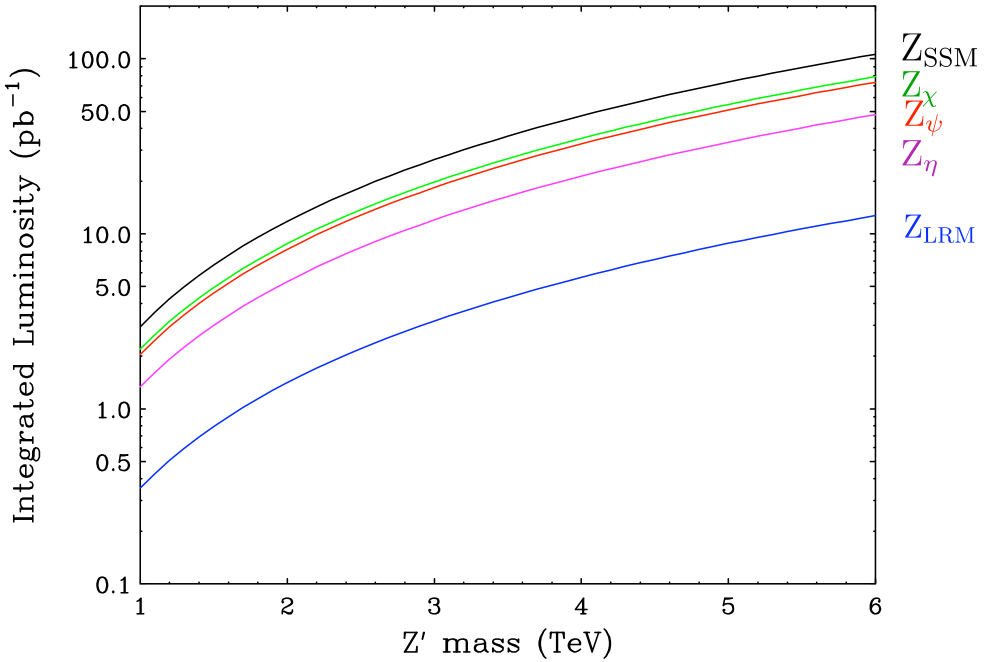
$$\sigma(E) = \frac{2J+1}{(2S_1+1)(2S_2+1)}\frac{4\pi}{k^2}\left[\frac{\Gamma^2/4}{(E-E_0)^2+\Gamma^2/4}\right]B_{in}B_{out}$$

Convolute with beam resolution ΔE.
If ΔE« Γ

$$\boxed{R_{\text{peak}} = (2J+1)3\frac{B(\mu^+\mu^-)B(visible)}{\alpha^2_{\text{EM}}}}$$



- Can use to set minimum required luminosity
  - Likely new physics candidates:
    - scalars: h, H^0, A^0,...
    - gauge bosons: Z′
    - new dynamics: bound states
    - ED: KK modes
  - Example - new gauge boson: Z′
    - SSM, E6, LRM
    - 5σ discovery limits: 4-5 TeV at LHC (@ 300 fb^{-1})

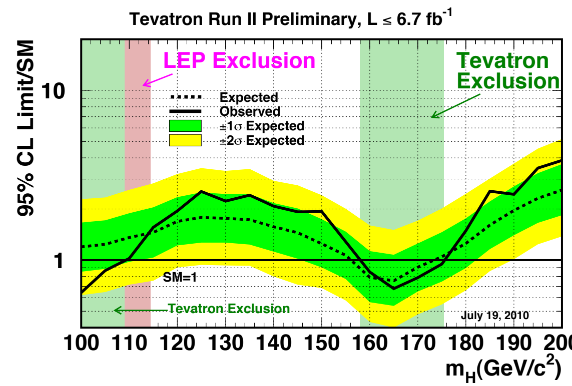


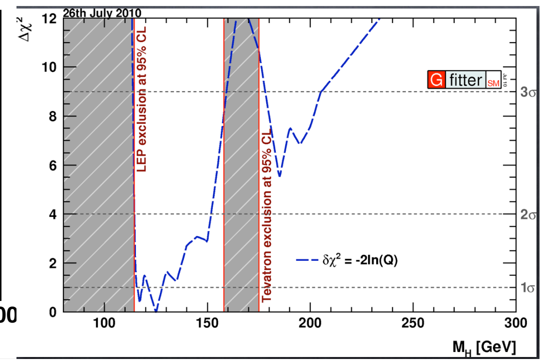
The integrated luminosity required to produce 1000 $\mu^+\mu^-$ -> Z′ events on the peak

Minimum luminosity at Z′ peak:
$\mathcal{L}$ = 0.5-5.0 x 10^{30} cm^{-2} sec^{-1}
for M(Z′) -> 1.5-5.0 TeV

Higgs Boson

- SM Higgs constraints:
  - Direct: LEP $m_H > 114.7$ GeV (95% CL)
    CDF/D0 $m_H < 158$ or > 175 GeV (95% CL)
  - Indirect: LEP/SLC $m_H < 190$ GeV (95% CL)
  - Combined: Gfitter
    $114.6 < m_H < 151.8$ GeV ($2\,\sigma$)

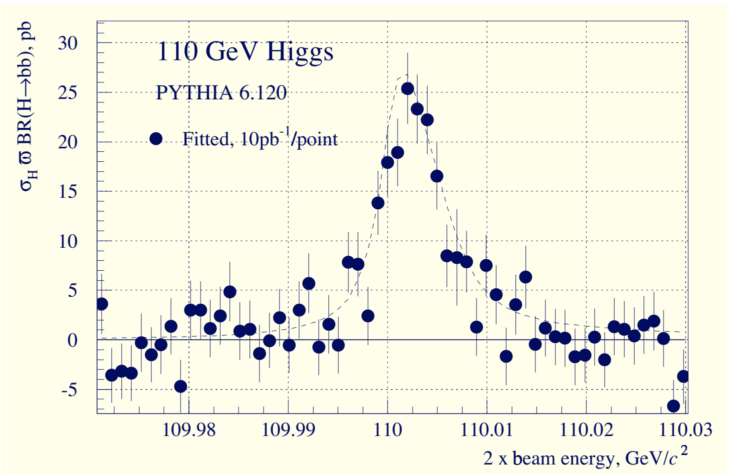




- Higgs discovery LHC ->
  - Higgs boson couplings?
  - Higgs self-couplings?
  - Any additions scalars? EW doublets, triplets or singlets?
  - Where's the next scale?

- For low energy muon collider
  - s-channel Higgs production
    - Coupling to lepton mass: $[\frac{m_\mu}{m_e}]^2 = 4.28 \times 10^{\,4}$
    - Narrow width: $m_h = 120 \text{ GeV} \to \Gamma = 3.6 \text{ MeV}$
  - Direct Higgs width measurement:

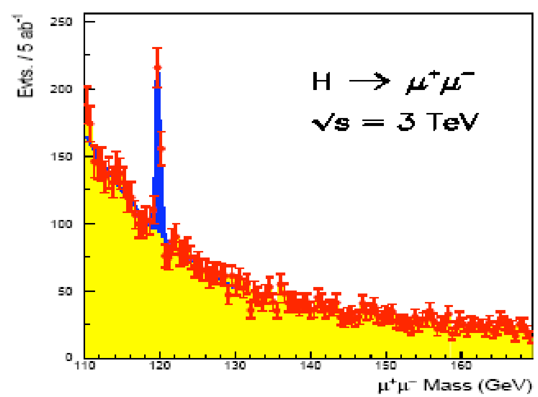
$$\Delta E/E \approx 0.003\% \ \text{ and } 100\ pb^{-1}$$



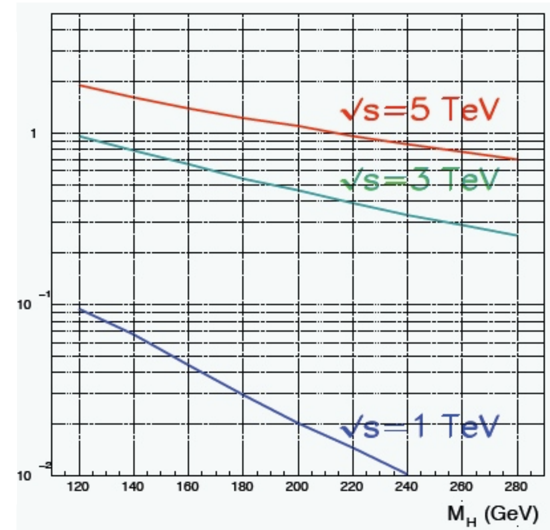
Higgs Boson

- Various processes available for studying the Higgs at a multi-TeV muon collider
  - associated production: Zh^0
    - R ~ 0.12
    - search for invisible h^0 decays
  - Higgsstrahlung: tth^0
    - R ~ 0.01 needs 10 ab^{-1}
    - measure top coupling
  - W^*W^* fusion (m_h = 120 GeV)
    - $\nu_\mu\bar{\nu}_\mu h^0$: R ~ 1.1 s ln(s) (s in TeV^2)
    - $\nu_\mu\bar{\nu}_\mu h^0h^0$: measure Higgs self couplings

m(H) = 120 GeV



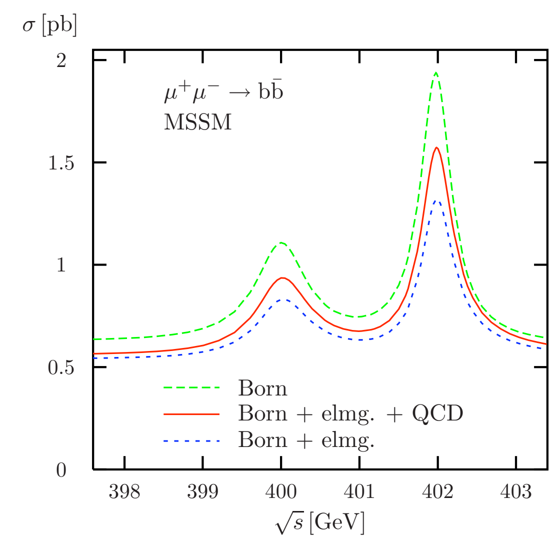
$\sigma(\mu^+\mu^- \to \nu\bar{\nu} h^0h^0)$ (fb^{-1})



MC or CLIC:
good benchmark process

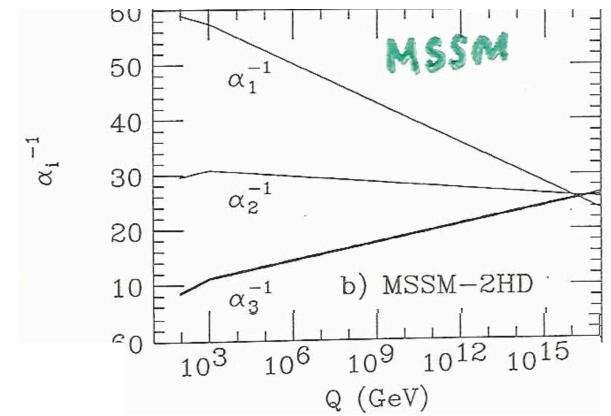
- Two Higgs Doublet Model (MSSM)
  - h^0, H^0, A^0, $H^\pm$
  - Decoupling limit: $M_A \gg M_Z$
    - h^0 couplings near SM Higgs values
    - H^0, A^0, $H^\pm$ masses nearly degerate
  - Precise energy resolution needed to resolve H^0, A^0 states

Dittmaier and Kaiser [hep-ph/0203120]



Supersymmetry

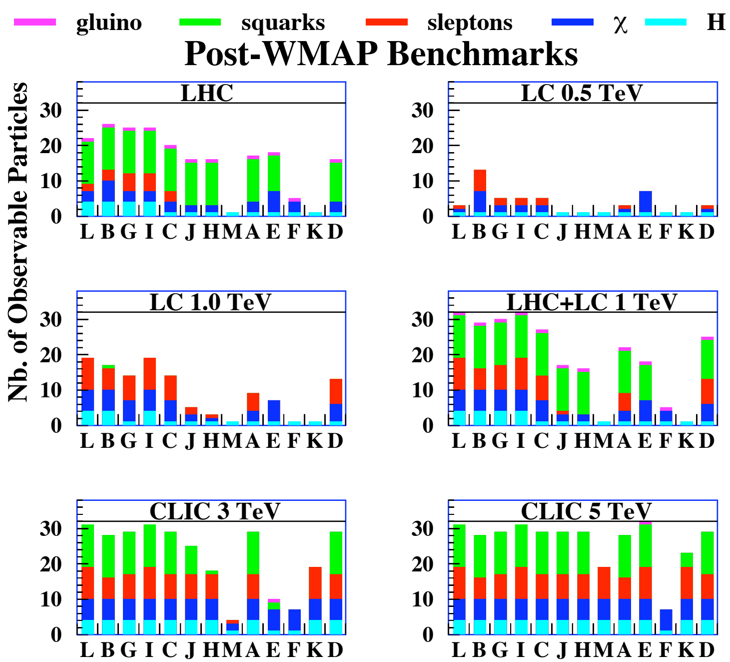
- Supersymmetry
  - Couplings of sparticles determined by symmetry. Masses depend on SUSY breaking mechanism.
  - If discovered at LHC ->
    - What is the spectrum of superpartner masses?
    - Dark matter candidates?
    - Are all the couplings correct?
    - What is the structure of flavor mixing interactions?
    - Are there additional CP violating interactions?
    - Is R parity violated?
    - What is the mass scale at which SUSY is restored?
    - What is the mechanism of SUSY breaking?



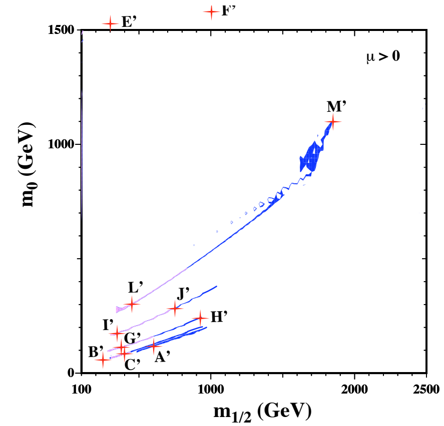
- cMSSM [Constrained Minimal Supersymmetric Standard Model]
  - Five parameters: m_0, $m_{1/2}$, $\tan\beta$, A/m_0, sign(μ)
  - Experimental constraints
    - Direct limit (LEP, CDF, Dzero): $m_{h^0}, m_{\chi^+}, m_{\tilde{t}}, \ldots$
    - Electroweak precision observables (EWPO): $M_W^2, \sin^2\theta_{sw}, (g-2)_\mu, \ldots$
    - B physics observables (BPO): $b \to s + \gamma,\ \mathrm{BR}(B_s \to \mu^+\mu^-), \ldots$
    - Cold dark matter (CDM): $\Omega_{DM} = .23 \pm .04$
  - Allowed regions are narrow filaments in parameter space

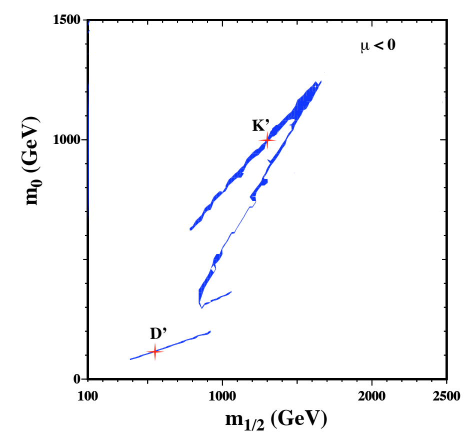
Supersymmetry

- The combination of the LHC and a multiTeV lepton collider is required to fully study the SUSY spectrum.
  - cMSSM 2004 CLIC study SUSY reach



Allowed regions and sample points





Similar Conclusion for MC

Anupama Atre, Low Emittance Muon Collider Workshop, Fermilab, April 2008

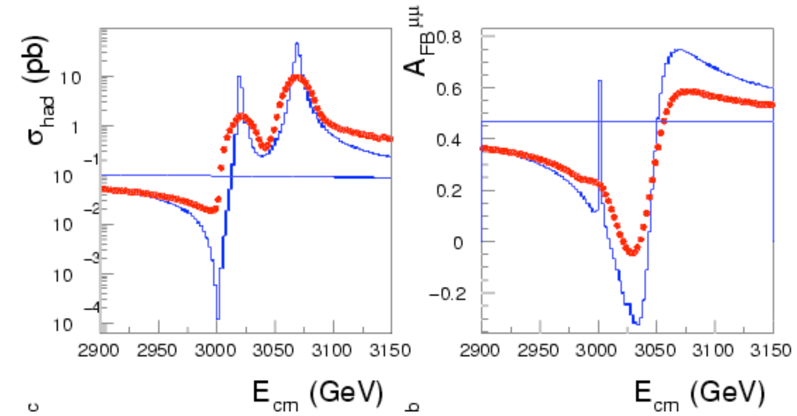
  - Alternate supersymmetry breaking schemes (mGMSB, mAMSB) also require multiTeV lepton collider. S. Heinemeyer, X. Miao, S. Su, G. Wieglein [arXiv:0805.2359]

- Supersymmetry provides a strong case for a multiTeV muon collider

New Strong Dynamics

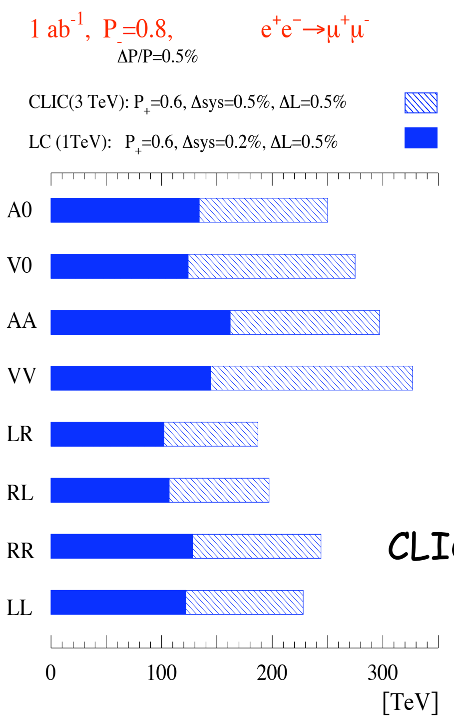
- A new strong interaction at the TeV scale
  - What is the spectrum of low-lying states?
  - What is the ultraviolet completion?
  - Any new insight into fermion flavor mixing and CP violation? , …

CLIC – D-BESS model (resolution 13 GeV)



Technicolor, ETC, Walking TC, Topcolor, …

- Technipions – s channel production (Higgs like)
- Technirhos – Nearby resonances (ρ_T,ω_T)
- Need fine energy resolution of muon collider.



CLIC Study

- New contact interaction: Composite quarks

$$\mathcal{L} = \frac{4\pi}{\Lambda^2}(\bar{\Psi}\Gamma\Psi)(\bar{\Psi}\Gamma'\Psi)$$

  - Both MC and CLIC probe scales Λ > 200 TeV

    Muon Collider Study

    E.Eichten, S.~Keller, [arXiv:hep-ph/9801258]
  - MC - forward cone cut | θ | > 20° little effect on limits
  - Polarization useful to disentangle chiral nature of interaction. good benchmark processes

Extra Dimensions

- Solves the Naturalness Problem: The effective GUT scale is moved closer.

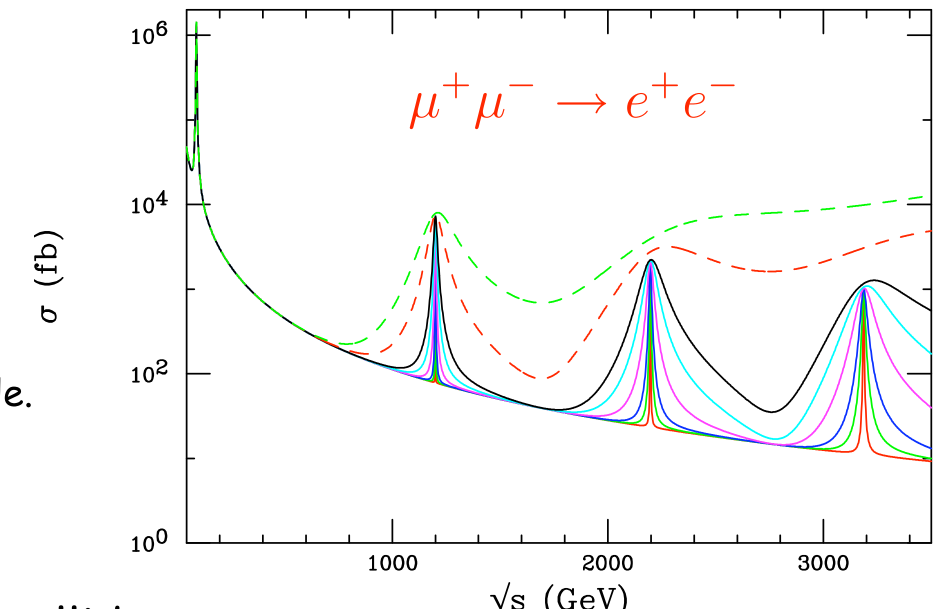
Theoretical issues

- How many dimensions?
- Which interactions (other than gravity) extend into the extra dimensions?
- At what scale does gravity become a strong interaction?
- What happens above that scale?
- ...

Randall-Sundrum model:
warped extra dimensions

- two parameters:
  - mass scale ∝ first KK mode;
  - width ∝ 5D curvature / effective 4D Planck scale.

possible KK modes



LHC discovery - Detailed study at a muon collider

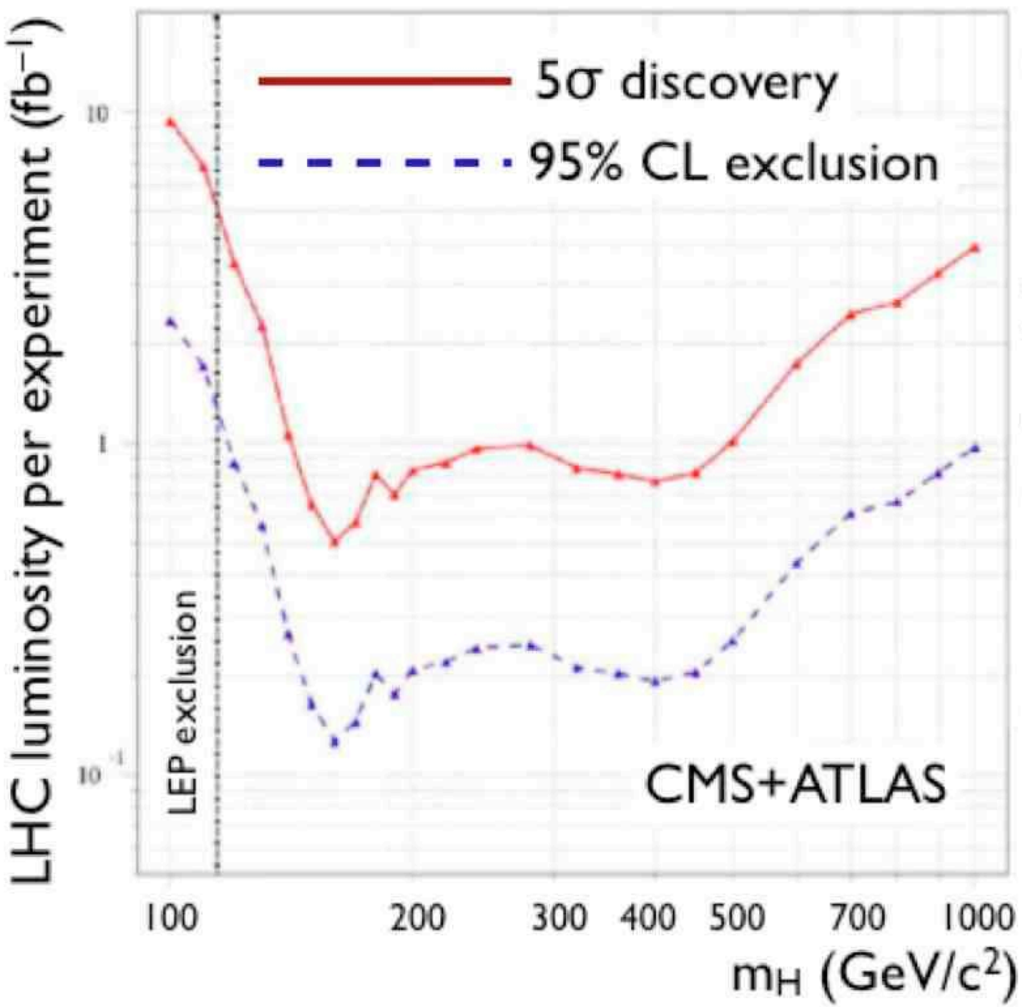
Summary

- A multiTeV lepton collider is required for full coverage of Terascale physics.
- The physics potential for a muon collider at $\sqrt{s} \sim 3$ TeV and integrated luminosity of 1 ab^{-1} is outstanding. Particularly strong case for SUSY and new strong dynamics.
- Narrow s-channel states played an important role in past lepton colliders. If such states exist in the multi-TeV region, they will play a similar role in precision studies for new physics. Sets the minimum luminosity scale.
- A staged Muon Collider can provide a Neutrino Factory to fully disentangle neutrino physics.
- A detailed study of physics case for 1.5-4.0 TeV muon collider has begun. Goals:
  - Identify benchmark processes: pair production (slepton; new fermion), Z′ pole studies, h^0 plus missing energy, resolving nearby states (H^0-A^0; ρ_T-ω^0_T), ...
  - Dependence on initial beam [electron/muon, polarization and beam energy spread] as well as luminosity to be considered.
  - Estimates of collision point environment and detector parameters needed.
  - Must present a compelling case even after ten years of running at the LHC.

  http://www.fnal.gov/directorate/Longrange/Steering_Public/workshop-muoncollider.html

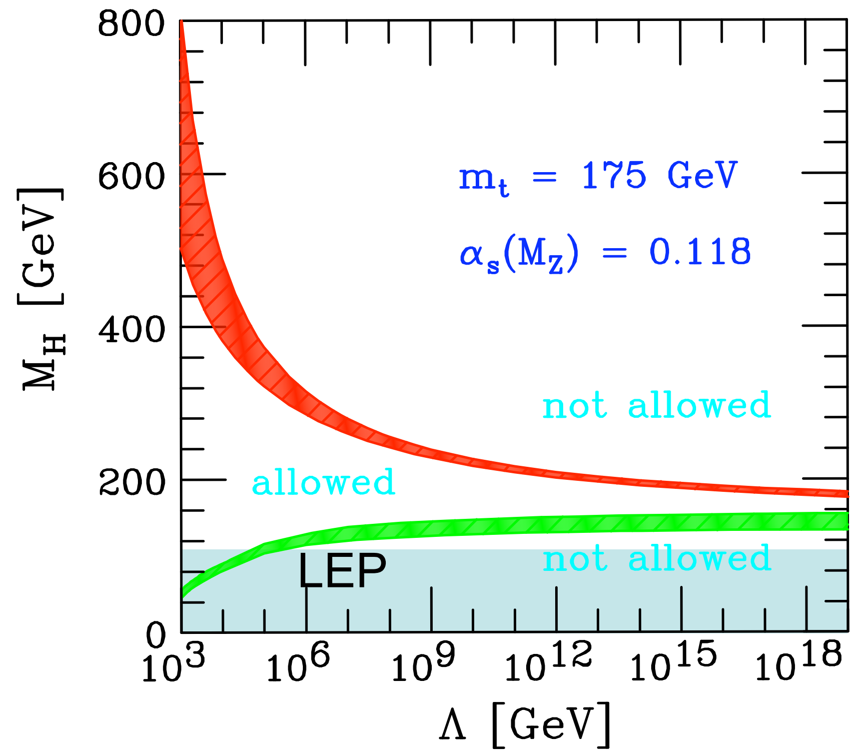
Backup Slides

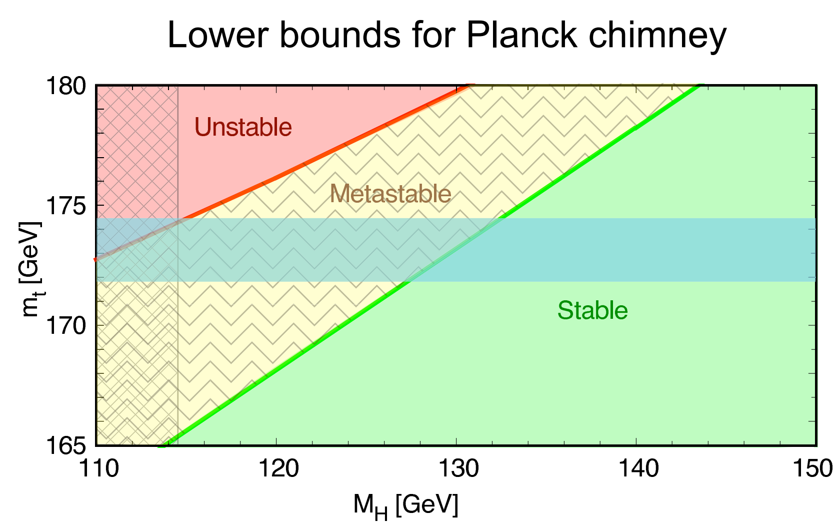
LHC - Discovery of the SM Higgs



Constraints on Standard Model Higgs

- Theoretical Constraints:
  - The standard model with an elementary Higgs scalar is only self-consistent up to some maximum energy scale (Λ).
  - Upper bound - A large Higgs mass requires a large higgs self-coupling term. This coupling increases with the scale Λ until perturbative theory breaks down.
  - Lower bound - For small Higgs mass, the quantum corrections can lead to vacuum instability.
  - Planck Chimney: SM self-consistent to Planck scale ($\approx 10^{19}$ GeV)



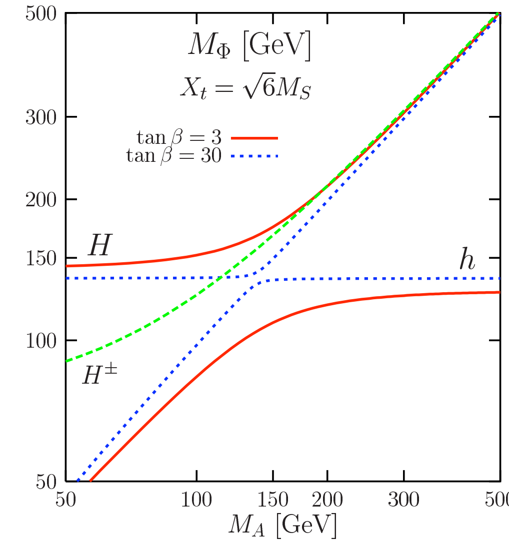


Two Higgs Doublets (MSSM)

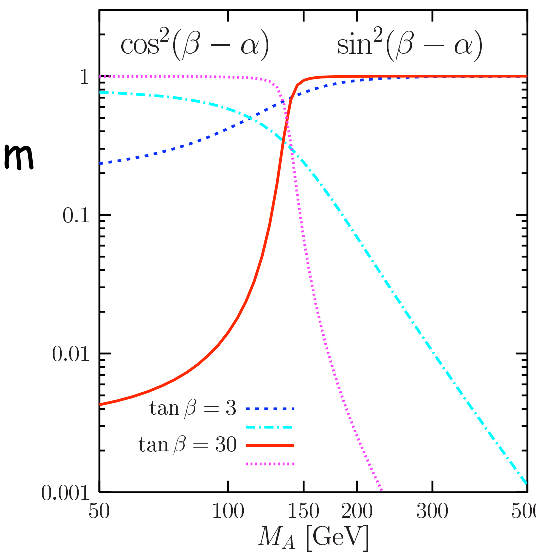
- decay amplitudes depend on two parameters:

	$\mu^+\mu^-, b\bar{b}$	$t\bar{t}$	ZZ, W^+W^-	ZA^0
h^0	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$
H^0	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos(\beta-\alpha)$	$-\sin(\beta-\alpha)$
A^0	$-i\gamma_5\tan\beta$	$-i\gamma_5/\tan\beta$	0	0

$$\tan 2\alpha = \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}\tan 2\beta.$$



- decoupling limit $m_{A^0} >> m_{Z^0}$:
  - h^0 couplings close to SM values
  - H^0, $H^\pm$ and A^0 nearly degenerate in mass
  - H^0 small couplings to VV, large couplings to ZA^0
  - For large $\tan\beta$, H^0 and A^0 couplings to charged leptons and bottom quarks enhanced by $\tan\beta$. Couplings to top quarks suppressed by $1/\tan\beta$ factor.



- good energy resolution is needed for H^0 and A^0 studies:
  - for s-channel production of H^0 : $\Gamma/M \approx 1\%$ at $\tan\beta = 20$.
  - nearby in mass need good energy resolution to separate H and A.
  - can use bremsstrahlung tail to see states using bb decay mode.

good benchmark process

- Good energy resolution is needed for H^0 and A^0 studies:
  - for s-channel production of H^0 : $\Gamma/M \approx 1\%$ at $\tan\beta = 20$.
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  - can use bremsstrahlung tail to see states using bb decay mode

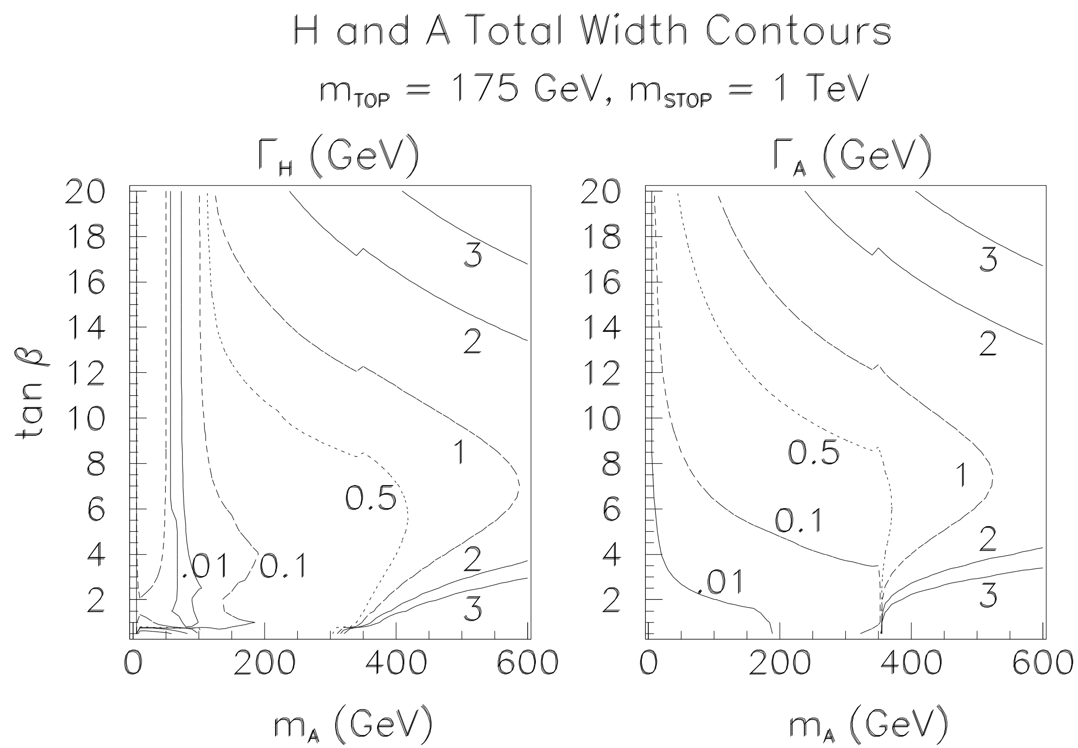
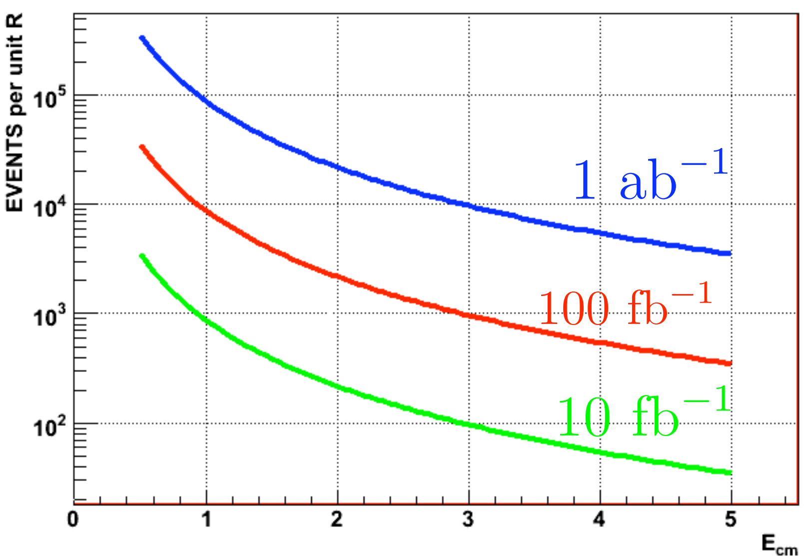


Figure 20: Contours of H^0 and A^0 total widths (in GeV) in the $(m_{A^0}, \tan\beta)$ parameter space. We have taken $m_t = 175$ GeV and included two-loop/RGE-improved radiative corrections using $m_{\tilde{t}} = 1$ TeV and neglecting squark mixing. SUSY decay channels are assumed to be absent.

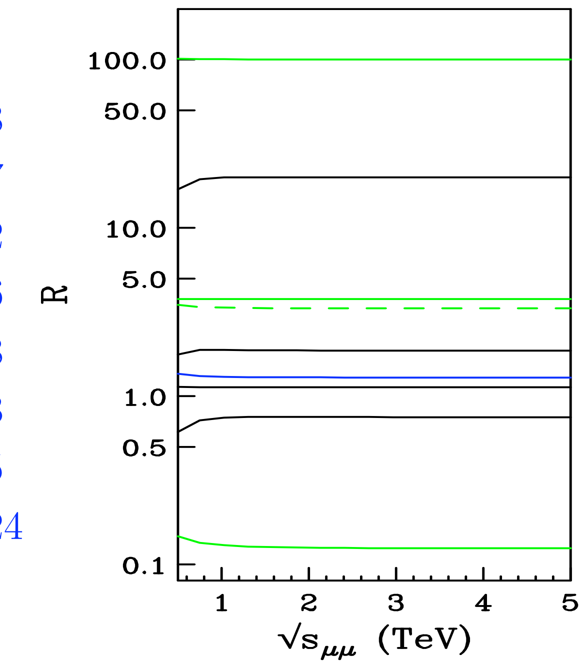
Multi-TeV Muon Collider Basics

- For $\sqrt{s} > 500$ GeV
  - Above SM pair production thresholds:
    R ≡ σ/σ_{QED} ($\mu^+\mu^-\to e^+e^-$) flat
- Luminosity Requirements



R at $\sqrt{s}$ = 3 TeV
$O(\alpha_{em}^2)$ $O(\alpha_s^0)$

$$\begin{aligned}
\mu^+\mu^-(20^\circ\ \mathrm{cut}) &= 100 \\
W^+W^- &= 19.8 \\
\gamma\gamma &= 3.77 \\
Z\gamma &= 3.32 \\
t\bar{t} &= 1.86 \\
b\bar{b} &= 1.28 \\
e^+e^- &= 1.13 \\
ZZ &= 0.75 \\
Zh(120) &= 0.124
\end{aligned}$$



(one unit of R)

$$\sigma_{\mathrm{QED}}(\mu^+\mu^-\to e^+e^-) = \frac{4\pi\alpha^2}{3s} = \frac{86.8\ \mathrm{fb}}{s(\mathrm{TeV}^2)}$$

For example: $\sqrt{s} = 3.0\ \mathrm{TeV}$ $\Rightarrow$ 965 events/unit of R

$$\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1} \to 100\ \mathrm{fb}^{-1}\mathrm{year}^{-1}$$

Processes with R ≥ 0.1 can be studied

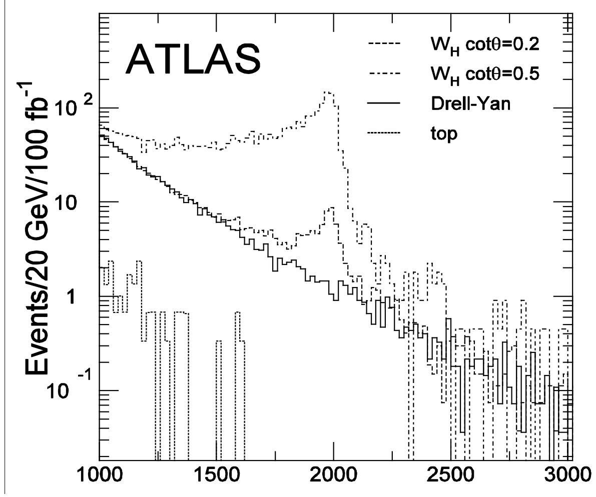
Total - 128 K SM events per year

New Fermions and Gauge Bosons

- Present CDF/D0 bounds on W', Z', and new quarks effectively rule out production at ILC.

State	CDF/D0 Limit (GeV)
Quark: (W,Z,h) + jet	335
Z' (SM)	1071
W' (SM)	860

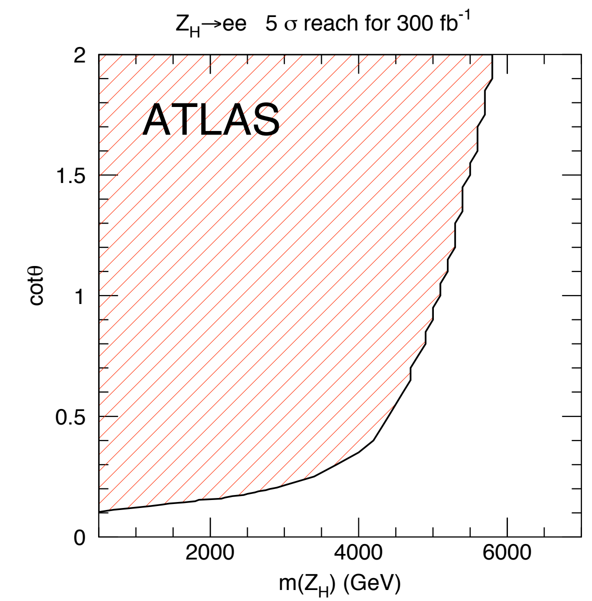
ATLAS study LHC [hep-ph/0402037]



- Littlest Higgs Model: good benchmark processes

  charge (2/3) quark T (EW singlet),
  new W, Z, and A gauge bosons, Higgs triplet

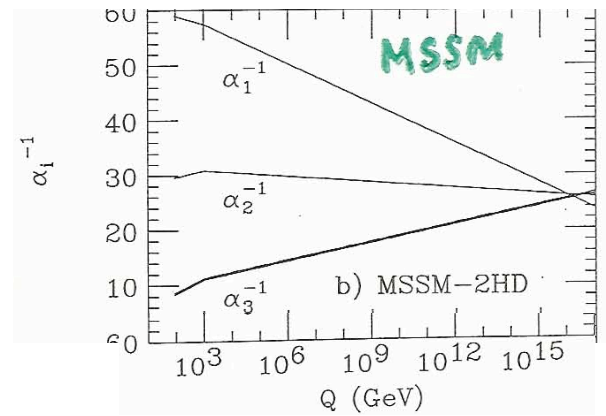
  At the LHC, T observable for m(T) < 2.5 TeV
  For W, Z, and A dependent on mixing parameters



- Muon collider will allow detailed study. Requires high luminosity 1 ab^{-1} for T

Supersymmetry

- Supersymmetry
  - Q_{susy} |boson> = |fermion>: gluon -> gluino ,... ; W boson -> wino; higgs -> higgino, ...
    Q_{susy} |fermion>=|boson>: top quark -> top squark (L,R), ...; electron -> selectron(L,R), ...
    - spin 1/2 symmetry charges $\{\bar{Q}_{susy}, Q_{susy}\} = 2\,\gamma^{\mu} P_{\mu}$; $Q_{susy}\,H|state\rangle = H\,Q_{susy}|state\rangle$
  - supersymmetry dictates the couplings between particles and sparticles
  - supersymmetry is broken $M_{sparticle} \neq M_{particle}$



- Solves the hierarchy and GUT unification problems

- Theoretical issues after discovery at the LHC :
  - What is the spectrum of superpartner masses?
  - Dark matter candidates?
  - Are all the couplings correct?
  - What is the structure of flavor mixing interactions?
  - Are there additional CP violating interactions?
  - Is R parity violated?
  - What is the mass scale at which SUSY is restored?
  - What is the mechanism of SUSY breaking?

Names		spin 0	spin 1/2	$SU(3)_c$, $SU(2)_L$, $U(1)_y$
squarks, quarks (× 3 families)	Q	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)	$\mathbf{3}$, $\mathbf{2}$, 1/3
	$\bar{u}$	$\tilde{\bar{u}}_L(\tilde{u}_R)$	$\bar{u}_L \sim (u_R)^c$	$\bar{\mathbf{3}}$, $\mathbf{1}$, -4/3
	$\bar{d}$	$\tilde{\bar{d}}_L(\tilde{d}_R)$	$\bar{d}_L \sim (d_R)^c$	$\bar{\mathbf{3}}$, $\mathbf{1}$, 2/3
sleptons, leptons (× 3 families)	L	$(\tilde{\nu}_{eL}, \tilde{e}_L)$	(ν_{eL}, e_L)	$\mathbf{1}$, $\mathbf{2}$, -1
	$\bar{e}$	$\tilde{\bar{e}}_L(\tilde{e}_R)$	$\bar{e}_L \sim (e_R)^c$	$\mathbf{1}$, $\mathbf{1}$, 2
higgs, higgsinos	H_u	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$	$\mathbf{1}$, $\mathbf{2}$, 1
	H_d	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$	$\mathbf{1}$, $\mathbf{2}$, -1

Table 1: Chiral supermultiplet fields in the MSSM.

Names	spin 1/2	spin 1	$SU(3)_c$, $SU(2)_L$, $U(1)_y$
gluinos, gluons	$\tilde{g}$	g	$\mathbf{8}$, $\mathbf{1}$, 0
winos, W bosons	$\tilde{W}^{\pm}, \tilde{W}^0$	$W^{\pm}, W^0$	$\mathbf{1}$, $\mathbf{3}$, 0
bino, B boson	$\tilde{B}$	B	$\mathbf{1}$, $\mathbf{1}$, 0

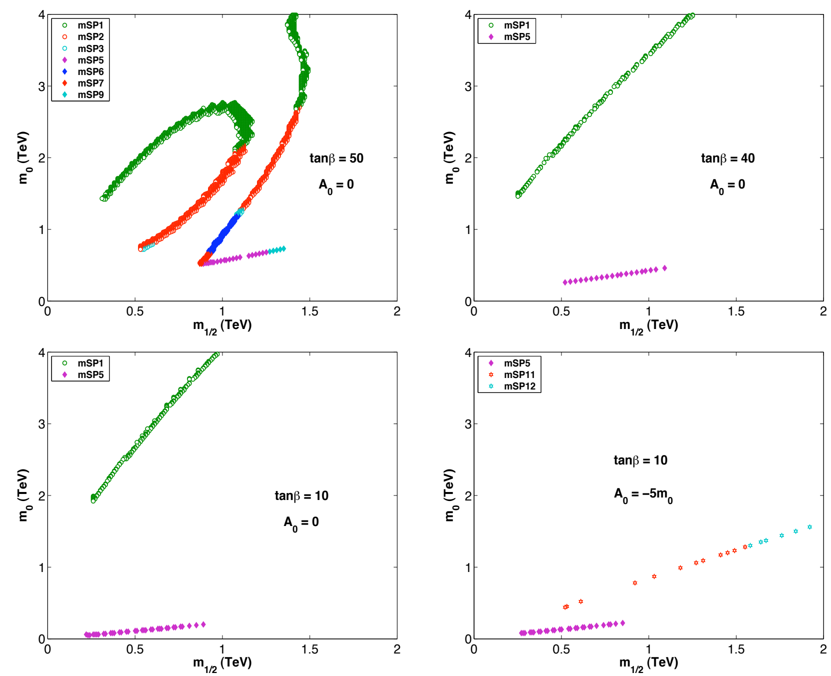
Table 2: Gauge supermultiplet fields in the MSSM.

cMSSM

- Many studies of constraints on cMSSM
  - Present experimental constraints
    - Direct limit (LEP, CDF, Dzero): $m_{h^0}, m_{\chi^+}, m_{\tilde{t}}, \ldots$
    - Electroweak precision observables (EWPO): $M_W^2, \sin^2\theta_{sw}, (g-2)_\mu, \ldots$
    - B physics observables (BPO): $b \to s+\gamma,\ \mathrm{BR}(B_s \to \mu^+\mu^-), \ldots$
    - Cold dark matter (CDM): $\Omega_{DM} = .23 \pm .04$
  - Allowed regions are narrow filaments in parameter space
  - Theoretical fine tuning

Monte Carlo searches of parameter space

J. Ellis, S. Heinemeyer, K.A. Olive, A.M. Weber, G. Wieglein [arXiv:0706.0652] ;
D. Feldman, Zuowei Lui and Pran Nath, PRL 99, 251802 (07); [arXiv:0802.4085] ; ...



$M_{h0} > 113.8 \Rightarrow$ large m_{stop}

requires large cancellations in the Higgs potential
$\Rightarrow$ fine tuning (to a few %)

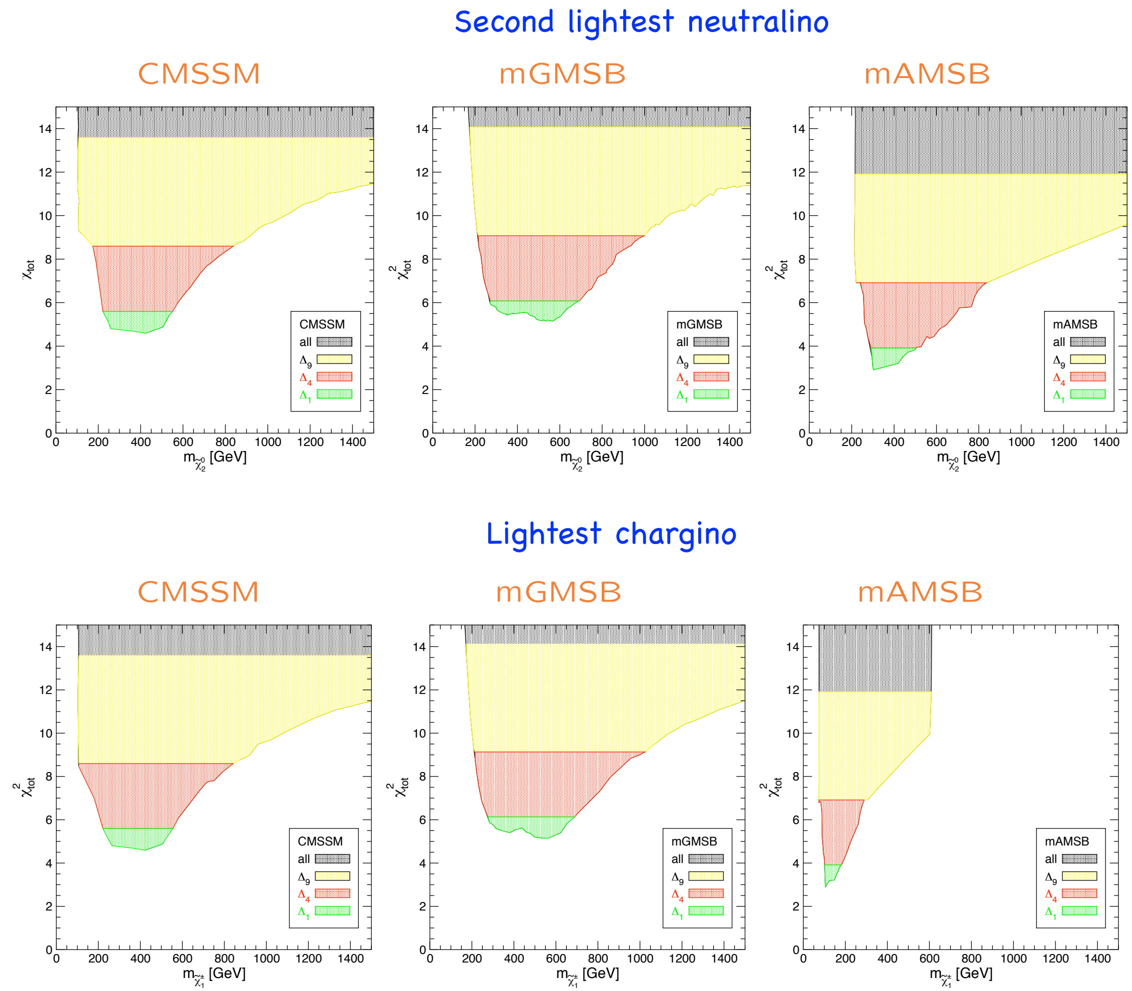
tree 1-loop

$$M_{h^0}^2 = m_Z^2\cos^2(2\beta) + \frac{3}{4\pi^2}\sin^2\beta\, y_t^2\Big[m_t^2\ln\left(m_{\tilde{t}_1}m_{\tilde{t}_2}/m_t^2\right) + c_{\tilde{t}}^2 s_{\tilde{t}}^2(m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)\ln(m_{\tilde{t}_2}^2/m_{\tilde{t}_1}^2)$$
$$+ c_{\tilde{t}}^4 s_{\tilde{t}}^4\Big\{(m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)^2 - \frac{1}{2}(m_{\tilde{t}_2}^4 - m_{\tilde{t}_1}^4)\ln(m_{\tilde{t}_2}^2/m_{\tilde{t}_1}^2)\Big\}/m_t^2\Big].$$

cMSSM, mGMSB, mAMSB Studies

- More generally, full coverage likely requires a multi TeV lepton collider

S. Heinemeyer, X. Miao, S. Su, G. Wieglein [arXiv:0805.2359]
(using only EWPO, BPO and LEP)



Second lightest neutralino:

m($\tilde{\chi}_2$) < 900 GeV for $\Delta\chi^2 < 4$
Heavy for LHC - possibly in decay chain ?
Lepton collider: $\chi_2^0 \rightarrow \chi_1^0 + X$

Lightest chargino:

m($\tilde{\chi}_1^+$) < 800, 900, 300 GeV for $\Delta\chi^2 < 4$
Heavy for LHC - possibly in decay chain ?
Lepton collider: Observable at ILC for mAMSB

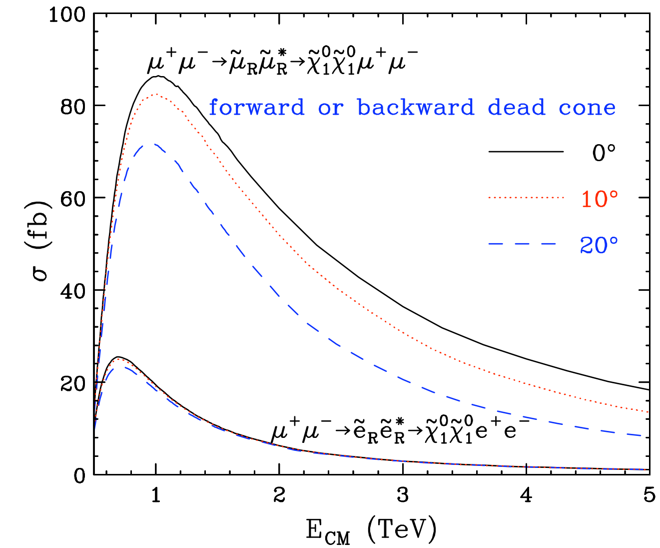
Lightest stop, sbottom and gluino:

m($\tilde{t}_1$) > 500 for $\Delta\chi^2 < 4$
Easy for LHC up to 2 TeV
Lepton collider: Detailed study?

Example Process at Muon Collider

- $\mu^+\mu^- \to \tilde{e}_1^+\tilde{e}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-$
  - Angular cut at 20° from beam direction:
    - 50% reduction for smuon pairs
    - 20% reduction for selectron pairs
  - Mass measurements using edge method better for MC than CLIC:

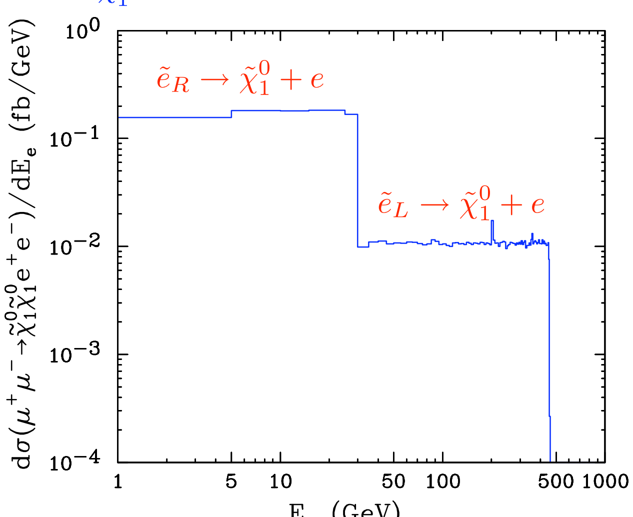
$$E_{\max/\min} = \frac{1}{2} M_{\tilde{e}} \left[1 - \frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{e}}^2} \right] \gamma(1 \pm \beta)$$



Effect of beamstrahlung

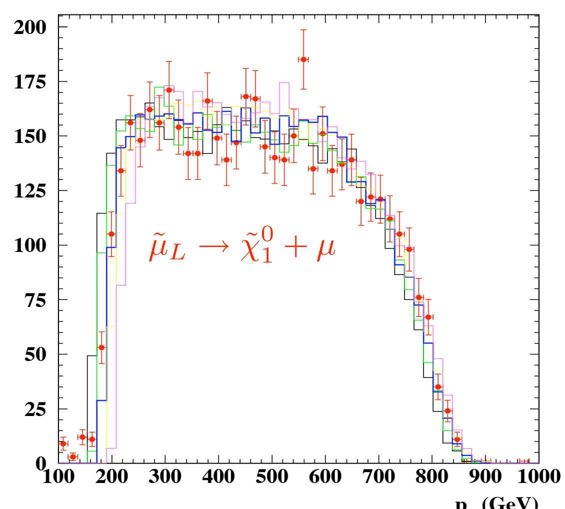
Kong, Winter (MC)

$m_{\tilde{\chi}_1^0} = 212;\ m_{\tilde{e}_R} = 222;\ m_{\tilde{e}_L} = 374$ GeV

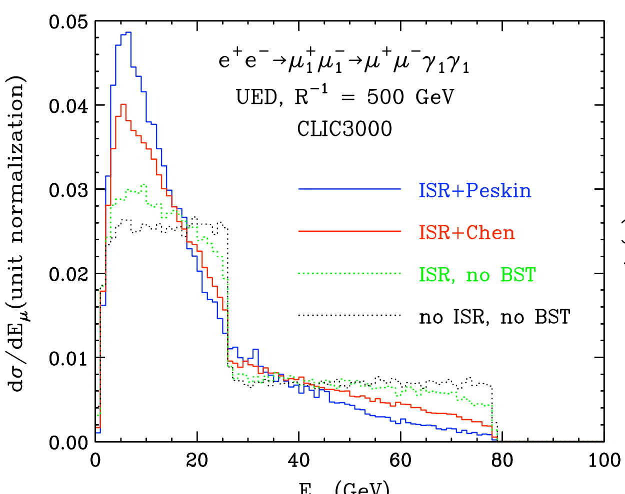


CLIC report (2004)

$m_{\tilde{\chi}_1^0} = 660$ GeV; $m_{\tilde{\mu}_L} = 1150$ GeV



Datta, Kong and Matchev [arXiv:hep-ph/0508161]



Goals of Neutrino Program

- Basic goals

  (a) Determine Dirac or Majorana nature of neutrinos.

  (b) Determine the mass hierarchy.

  (c) Measure θ_{13}, δ and improve θ_{12}, θ_{23} measurements

  (d) Study unitarity of PMNS matrix.

  (e) Are there additional mixing or CPV from new particles or interactions?

- Why is this important?

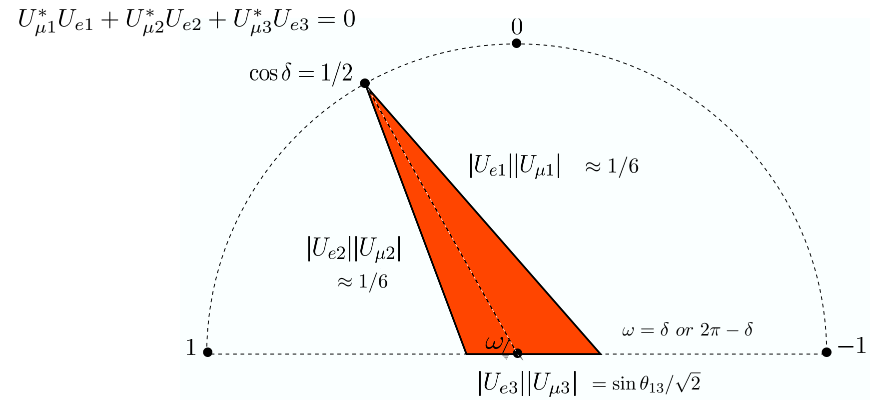
  (a) Neutrino masses are very small. Theoretical models for these masses predict new particles at the Terascale or a new scale beyond.

  (b) Potential source of lepton number violation and CP violation. Leptogenesis might be responsible the observed baryon asymmetry in the universe.

  (c) Contributions to dark matter and cosmological evolution.

  (d) Complimentary to energy frontier physics (LHC)

Unitarity Triangle:



$$|J| = 2 \times \mathcal{A}rea$$

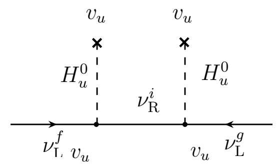
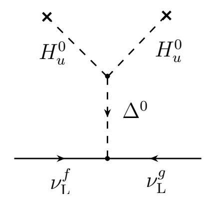
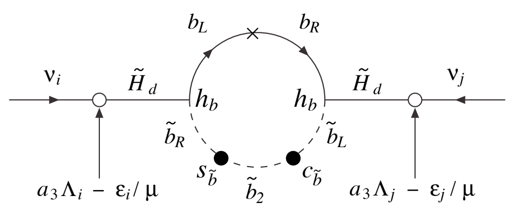
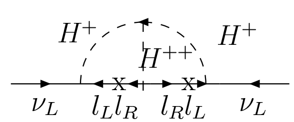
$$J = s_{12}c_{12}s_{23}c_{23}s_{13}c_{13}^2 \sin\delta$$

- Why a Neutrino Factory?

  (a) Large $\sin^2(2\theta_{13})$ ($\gtrsim 0.005$) - can explore new physics as subleading effects.
  (b) Small $\sin^2(2\theta_{13})$ - provides unmatched sensitivity.

Non-Standard Neutrino Interactions

- A plethora of theoretical models:

Model	Interaction	New Particles	Comments
(1-2-3) Seesaw I		ν_R, Majoron	Very light majoron dark matter candidate
(1-2-3) Seesaw II		heavy higgs triplet	
L-R Seesaw SU(3)×SU(2)×SU(2)×U(1)	Both types	new gauge bosons	No majoron B-L Terascale physics
SUSY models		SUSY partners	Calculable in terms of Smasses and Smixings. R parity violating
Babu model		charged $SU(2)_L$ singlet scalars	H^{++} scalar
Texture models, ...			